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DOI: <https://doi.org/10.1088/1742-6596/259/1/012022>

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ZORA URL: <https://doi.org/10.5167/uzh-46045>

Journal Article

Published Version



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Originally published at:

Palacios, J P (2010). LHCb: first results and prospects for the 2010-11 run. Journal of Physics: Conference Series, 259(1):012022.

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2010 J. Phys.: Conf. Ser. 259 012022

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# LHCb: first results and prospects for the 2010-11 run

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**Abstract.** The LHCb physics programme is now underway. The data collected in 2009 and in the first period of the 2010 run have allowed for a range of interesting minimum bias physics measurements, including those of prompt  $K_S^0$ , Lambda, anti-Lambda, proton and anti-proton production. Heavy flavour signals have also been collected and detailed studies of  $J/\psi$  production, both prompt and from B-decays, are underway. The status of these measurements will be reviewed, and the prospects will be given for the core LHCb CP-violation and rare decay programme in the remainder of the 2010-11 run.

## 1. Introduction

Beyond the standard model physics (BSM) predicts the existence of new particles at the TeV scale. These can be detected indirectly via appearance as virtual particles in loop and penguin diagrams contributing to electro-weak decays of heavy hadrons. This approach allows for the detection of such particles at energy scales lower than the kinematic limit for their direct production. It also provides knowledge of the phases in their couplings, giving information on the flavour structure of BSM physics. The LHCb detector [1] at the LHC collider is designed to search for new physics by precisely measuring elements of the CKM matrix as well as investigating rare flavour changing neutral current (FCNC) processes. In both approaches, the presence of new physics would manifest itself in deviations from the behaviour predicted by the standard model of particle physics (SM). This manuscript concentrates on the most important LHCb measurements for the first part of the 2010 run, based on  $14 \text{ nb}^{-1}$  of integrated luminosity.

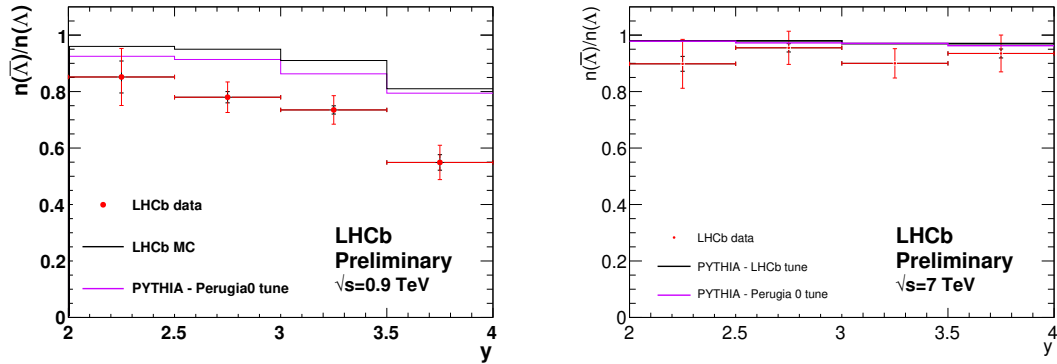
## 2. Key programme for 2010-2011 run

The core program of LHCb has been presented in detail in [2]. It consists of precise measurements of CKM parameters in CP violating decays, searches for FCNC processes that are extremely rare in the SM, measurements of production asymmetries in rare FCNC decays, and the measurement of anomalous polarisation in radiative B meson decays. With the  $1 \text{ fb}^{-1}$  of data predicted for the 2010-2011 run, it will be possible to make significant impact in all but the latter of these measurements. Furthermore, the early LHC running has provided an excellent opportunity to study CP violation effects in charm decays. Hence charm physics has become one of the key measurements for the 2010-2011 run.

### 2.1. Early data particle production

The emphasis during early running has been to understand the detector and trigger. This involved the measurement of the production rates well known hadrons, such as the  $K_S^0$ ,  $\Lambda$ ,  $D$

and  $\pi^0$  mesons to calibrate the momentum, energy scales and particle identification. Studies of di- $\mu$  final states, particularly the production of  $J/\Psi$  mesons [3], set the stage for studies of rare decays involving two muons in the final state. The production cross-section of  $K_s^0$  has been measured and published in [4]. The measurement of  $\bar{\Lambda}/\Lambda$  production ratios at the high  $\eta$  range of LHCb is important for the tuning of particle generators [5]. Its study is well underway. Figure 1 shows the  $\bar{\Lambda}/\Lambda$  production ratio at 0.9 and 7 TeV centre of mass energy. The ratio can be seen to be consistently lower than expected for  $\sqrt{s} = 0.9$  TeV.



**Figure 1.**  $\Lambda$  and  $\bar{\Lambda}$  production ratio as a function of rapidity  $y$  at 0.9 (left) and 7 TeV (right) centre of mass energy

## 2.2. Search for rare decays $B_s^0 \rightarrow \mu^+\mu^-$ , $D^0 \rightarrow \mu^+\mu^-$

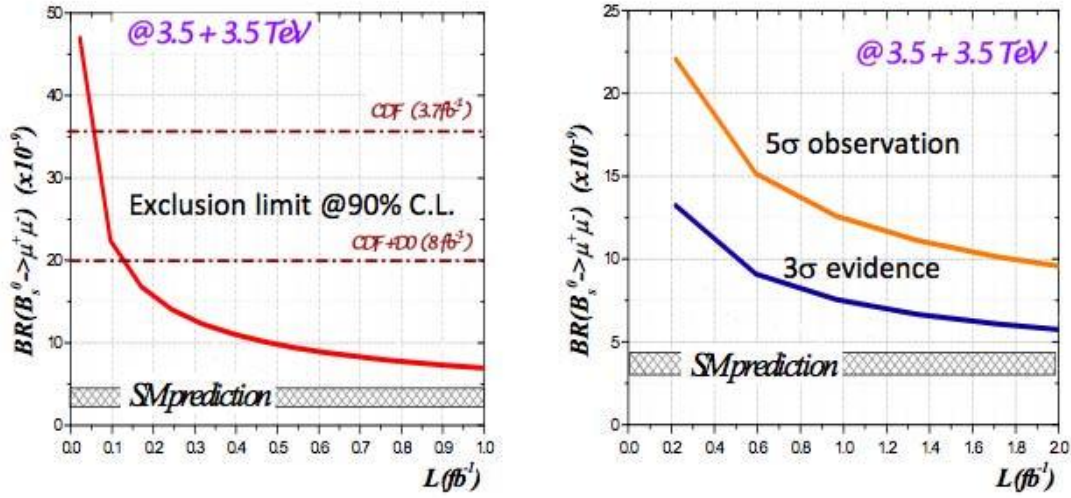
The decay channel  $B_s^0 \rightarrow \mu^+\mu^-$  has a branching ratio of  $\mathcal{B} = (3.35 \pm 0.32) \times 10^{-9}$  in the SM [6]. This rare decay mode can be greatly enhanced by physics beyond the standard model. For example, the minimal supersymmetric standard model (MSSM) predicts an enhancement as the sixth power if  $\tan\beta$ . The current experimental limit from CDF, based on  $3.7 \text{ fb}^{-1}$  of data, is  $\mathcal{B} < 3.6 \times 10^{-8}$  at 90% CL [7].

LHCb will select events such that the branching ratio can be estimated from data, without reliance on simulations. Three uncorrelated observables - the  $B_s^0$  invariant mass, muon likelihood, and geometrical likelihood - are used for selection. These can be calibrated with different control samples. The two-body invariant mass has been calibrated in early data using control channels  $K_S^0 \rightarrow \pi^+\pi^-$  and  $J/\psi \rightarrow \mu^+\mu^-$  decays. It is planned to calibrate the mass resolution at the mass scale of the  $B_s^0$  using the decay channel  $B_s^0 \rightarrow K^+K^-$ . Simulation studies show an expected resolution of around 20 MeV.

The branching ratio will be determined using control channels  $B^+ \rightarrow J/\psi K^+$  and  $B_d^0 \rightarrow K\pi$ . This requires an understanding of the ratio of  $B_s^0$  production over that of light  $B$  mesons,  $B_d^0$  and  $B_u^+$ , which can be obtained through a measurement of the relative rates of  $B_s^0 \rightarrow D_s^- \pi^+$  and  $B_d^0 \rightarrow D^- K^+$  [8].

LHCb expects a 90% confidence limit of  $16 \times 10^{-9}$  with  $0.2 \text{ fb}^{-1}$  of data. This compares favourably with the Tevatron expected limit for  $8 \text{ fb}^{-1}$ , as can be seen in Figure 2. With  $1.0 \text{ fb}^{-1}$  the LHCb exclusion limit will be down to  $\mathcal{B} = 7 \times 10^{-9}$ . Alternatively, the signal observation limit is expected to be for  $\mathcal{B}$  3.5 times the SM prediction.

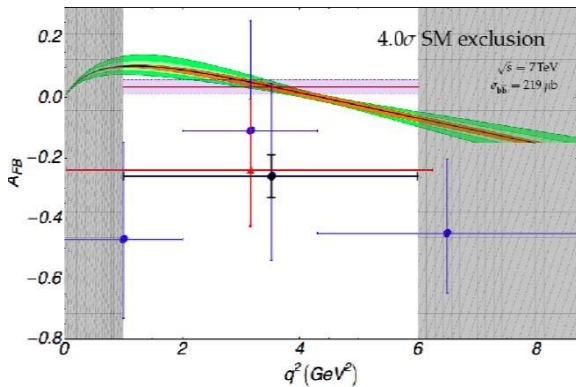
The decay channel  $D^0 \rightarrow \mu^+\mu^-$  presents similar characteristics to its  $B_s^0$  counterpart, with a SM branching fraction  $\mathcal{B} \approx 3 \times 10^{-13}$ . The Belle collaboration has measured  $\mathcal{B} < 1.4 \times 10^{-7}$  at 90% CL [9]. LHCb can improve on that limit, expecting to set an upper limit for  $\mathcal{B} < 4 \times 10^{-8}$  with only  $0.1 \text{ fb}^{-1}$ .



**Figure 2.** Left: the expected 90%  $B_s^0 \rightarrow \mu^+\mu^-$  branching fraction exclusion limit at LHCb as a function of integrated luminosity. The current and expected limits from the Tevatron are shown. Right: the expected 3 $\sigma$  observation and 5 $\sigma$  discovery branching fraction as a function of integrated luminosity. The SM prediction is shown.

### 2.3. Angular asymmetries in $B_d^0 \rightarrow K^*\mu^+\mu^-$

The  $B_d^0 \rightarrow K^*\mu^+\mu^-$  decay has a branching fraction of  $1.0 \times 10^{-6}$  in the SM. The angular distributions of the final state particles contain information on the couplings of virtual particles in loops contributing to the decay, and are well constrained within the SM. Therefore the angular distributions provide a probe for new physics.

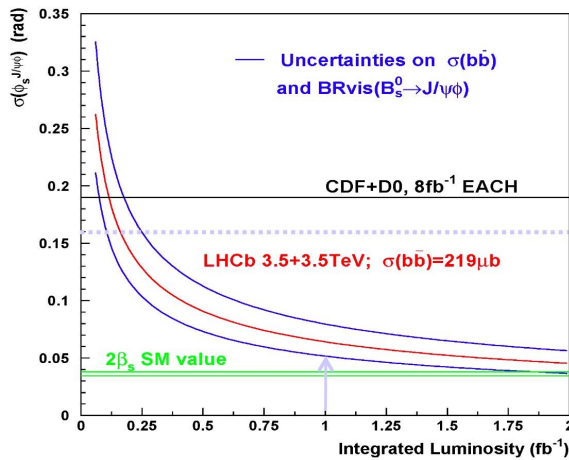


**Figure 3.**  $A_{FB}$  in  $B_d^0 \rightarrow K^*\mu^+\mu^-$  as a function of  $q^2$ . Standard model prediction (black line with red and green error bands) and average (purple line) for  $A_{FB}(q^2)$ , Belle data (blue points), BaBar data (red point), and predicted LHCb result (black point) assuming Belle measured value and  $1.0 \text{ fb}^{-1}$  of integrated luminosity.

The zero crossing point of the forward-backward asymmetry of the  $\mu^+\mu^-$  as a function of the  $q^2$  of the muons,  $A_{FB}(q^2)$ , has minimal hadronic uncertainties and high sensitivity to new couplings, and therefore is an optimal experimental observable. The standard model prediction, together with the current values from Belle and BaBar can be seen in Figure 3. These show an intriguing hint of a divergence from the SM. LHCb expects to find 1400 events in the first  $1.0 \text{ fb}^{-1}$  of data, leading to a sensitivity of  $\sigma(A_{FB}) = 0.07$ .

#### 2.4. $B_s$ mixing phase $\phi_s$

The decay  $B_s^0 \rightarrow J/\psi\phi$  is sensitive to the mixing phase  $\phi_s$  through the interference between mixing and decay amplitudes. The contribution from penguin diagrams to  $\phi_s$  is small, leading to a small theoretical error on the standard model prediction of  $\phi_s = (-36.0^{+1.6}_{-2.0})\text{mrad}$  [10]. New particles present in the box diagrams that give rise to  $B_s^0$  mixing can modify this phase, making it an ideal probe for new physics. The extraction of  $\phi_s$  from  $B_s^0 \rightarrow J/\psi\phi$  decays requires measuring the time dependent  $B_s^0$  and  $\bar{B}_s^0$  decay rates, thus requiring the tagging of the initial flavour of the  $B_s^0$ . Simulations show that LHCb has a mis-tag rate of 33% and an effective tagging efficiency of 6% in this channel. The fast oscillations of the  $B_s^0$  require a very high proper time resolution. LHCb expects 40 fs from simulation. This resolution can be measured from the negative edge of the proper time distribution of easily identifiable prompt decays, such as  $J/\psi \rightarrow \mu^+\mu^-$ . The  $J/\psi$  and  $\phi$  are both vector mesons. This means that they can be either in a CP-odd or CP-even final state, each of which has a different angular distribution for the final state particles. The extraction of the  $\phi_s$  phase requires that these components be extracted statistically. The procedure to do so shall be cross checked against  $B_d^0 \rightarrow J/\psi K^*$  decays, which share the same helicity structure and have been measured accurately in the  $B$  factories. Special attention has to be paid to angular biases introduced by trigger and selection cuts. The analysis can be complemented with  $B_s^0$  decays into final states such as  $J/\psi f_0$  and  $J/\psi \eta'$ , which are CP eigenstates. These have lower yields but do not require an angular analysis. LHCb expects some  $30 \times 10^3$   $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$  events in  $1.0\text{fb}^{-1}$ , resulting in a sensitivity of  $\sigma(\phi_s) = 0.07$ .

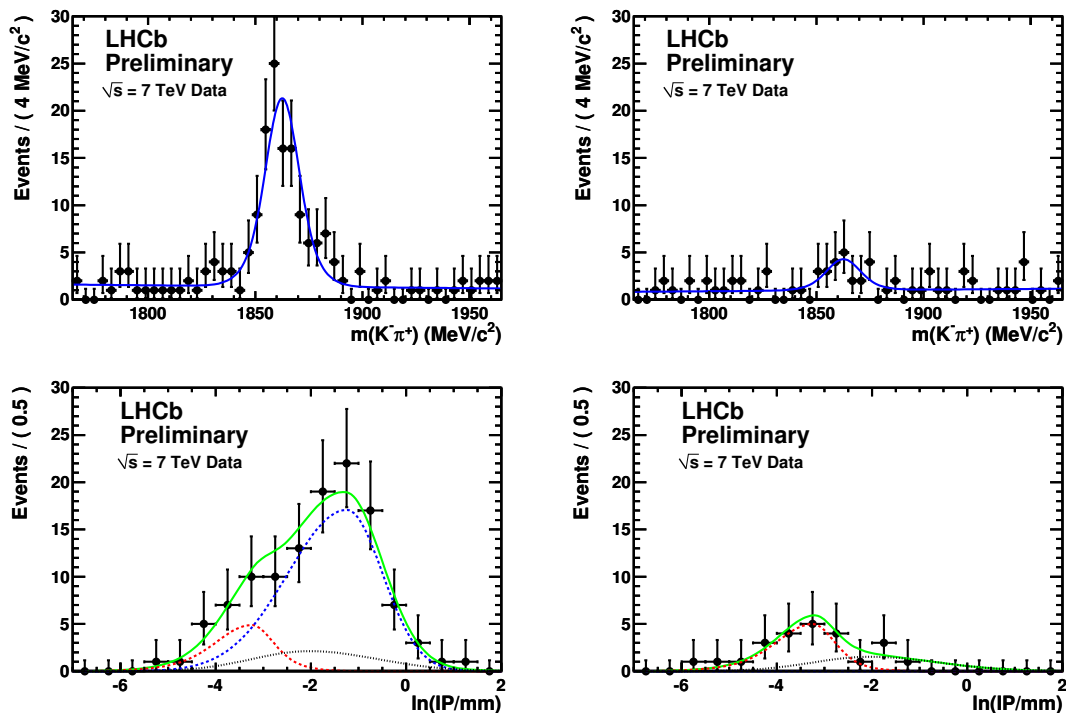


**Figure 4.** Sensitivity for  $\phi_s$  from  $B_s^0 \rightarrow J/\psi\phi$  as a function of integrated luminosity. The standard model prediction and Tevatron expected sensitivity for  $8\text{fb}^{-1}$  are shown. The expected LHCb sensitivity for the 2010-2011 run, corresponding to  $1.0\text{fb}^{-1}$ , is  $\sigma(\phi_s) \approx 0.07$ .

#### 2.5. Charm physics

LHCb expects to collect of the order of  $10^8$   $D$  mesons with  $1\text{fb}^{-1}$ , allowing for precise measurements of CP violation in  $D^0\bar{D}^0$  mixing and direct CP violation in decays of charged  $D$  mesons, both of which are small in the Standard Model. With only  $0.1\text{fb}^{-1}$ , 17 million tagged  $D^0 \rightarrow K\pi$  and 1.3 million tagged  $D^0 \rightarrow K^+K^-$  are expected, allowing to surpass the sensitivity on CP violation in  $D$  mixing currently available from  $B$  factories. Several million single Cabibbo suppressed  $D^+ \rightarrow K^+K^-\pi^+$  decays are expected, allowing for sensitive searches for direct CP violation. In both aspects, LHCb expects to surpass the results of the  $B$  factories with the data obtained in the 2010-2011 run.

The production of  $D^0$  mesons in channels with a well known branching fraction can be used to measure the  $b\bar{b}$  production cross section in  $pp$  collisions. In one such study,  $b \rightarrow D^0 X \mu^- \bar{\nu}$  decays have been identified and resolved from prompt  $D^0$  by using the impact parameter of the



**Figure 5.**  $D^0 \rightarrow K^-\pi^+$  invariant mass (top) and logarithm of the  $D^0$  impact parameter with respect to the primary vertex in millimeters (bottom) for  $D^0\mu$  candidates with 'right sign' (left) and 'wrong sign' (right) correlation, in  $3 \text{ nb}^{-1}$  of data at  $\sqrt{s} = 7 \text{ TeV}$ . Fit results are superimposed as curves. In the bottom plots, the black dotted curve represents the non- $D^0$  background estimated from the mass sidebands, and the blue and red dotted curves represent the  $D^0$  signal from b-hadron decays and from prompt production.

decay products with respect to the primary vertex. The charge of the  $\mu$  and the decay products of the  $D^0$  has been used to determine the combinatorial background component. Both aspects are illustrated in Figure 5. This analysis has been extended and published in [11].

### 3. Conclusions

The LHCb detector has successfully initiated its heavy flavour programme. The production and decays of well known particles has been used to understand the detector response and key elements of the core physics programme. We expect to improve on current experimental constraints on new physics in the flavour sector with  $0.2 \text{ fb}^{-1}$ . With the  $1.0 \text{ fb}^{-1}$  of integrated luminosity expected for the 2010-2011 run LHCb will be in a good position to find physics beyond the SM.

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